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### **Search for long-lived neutral particles decaying into lepton jets in proton-proton collisions at $\sqrt{s}=8$ TeV with the ATLAS detector**

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# Search for long-lived neutral particles decaying into lepton jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



## The ATLAS collaboration

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**ABSTRACT:** Several models of physics beyond the Standard Model predict neutral particles that decay into final states consisting of collimated jets of light leptons and hadrons (so-called “lepton jets”). These particles can also be long-lived with decay length comparable to, or even larger than, the LHC detectors’ linear dimensions. This paper presents the results of a search for lepton jets in proton-proton collisions at the centre-of-mass energy of  $\sqrt{s} = 8$  TeV in a sample of  $20.3 \text{ fb}^{-1}$  collected during 2012 with the ATLAS detector at the LHC. Limits on models predicting Higgs boson decays to neutral long-lived lepton jets are derived as a function of the particle’s proper decay length.

**KEYWORDS:** Hadron-Hadron Scattering

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## 1 Introduction

Several possible extensions of the Standard Model (SM) predict the existence of a hidden sector that is weakly coupled to the visible one (e.g. refs. [1–6]). Depending on the structure of the hidden sector and its coupling to the SM, some unstable hidden states may be produced at colliders and decay back to SM particles with sizeable branching fractions. For example, in supersymmetric theories, the lightest visible super-partner may decay into hidden particles, some of which can decay back to the visible sector (see e.g. refs. [2, 6, 7]). Several other distinct, non-supersymmetric, examples exist (see e.g. refs. [1, 3–5]). If the lightest unstable hidden states have masses in the MeV to GeV range, they would decay mainly to leptons and possibly light mesons.

An extensively studied case is one in which the two sectors couple via the vector portal, in which a light hidden photon (dark photon,  $\gamma_d$ ) mixes kinetically with the SM photon. If the hidden photon is the lightest state in the hidden sector, it decays back to SM particles with branching fractions that depend on its mass [6, 8, 9]. For the case in which the  $\gamma_d$  kinetically mixes with hypercharge, one finds that  $\epsilon$ , the kinetic mixing parameter, controls

both the  $\gamma_d$  decay branching fractions and lifetime. More generally, however, the branching fractions and lifetime are model-dependent and may depend on additional parameters.

Due to their small mass, these particles are typically produced with a large boost and, due to their weak interactions, can have non-negligible lifetime. As a result one may expect, from dark photon decays, collimated jet-like structures containing pairs of electrons and/or muons and/or charged pions (“lepton jets”, LJs) that can be produced far from the primary interaction vertex of the event (displaced LJs).

Neutral particles which decay far from the interaction point into collimated final states represent a challenge both for the trigger and for the reconstruction capabilities of the LHC detectors. Collimated charged particles in the final state can be difficult to disentangle due to the limited granularity of the detector. Moreover, in the absence of information from the inner tracking system, it is necessary to use the muon spectrometer (MS) for the reconstruction of tracks which originate from a secondary decay far from the primary interaction vertex (IP).

The high-resolution, high-granularity measurement capability of the ATLAS “air-core” MS is ideal for this type of search. In addition, the ATLAS inner tracking system can be used to define isolation criteria to significantly reduce, for decay vertices far from the interaction point, the otherwise overwhelming SM background from proton-proton collisions.

The search for displaced LJs presented in this paper employs the full dataset collected by ATLAS during the 2012 run at  $\sqrt{s} = 8$  TeV, corresponding to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . Related searches for prompt LJs have been performed both at the Tevatron [10, 11] and at the LHC [12–15]. Additional constraints on scenarios with hidden photons are extracted from, e.g., beam-dump and fixed-target experiments [16, 17, 17–27],  $e^+e^-$  colliders [28–30], B-factories [31, 32], electron and muon anomalous magnetic moment measurements [33–35] and astrophysical observations [36, 37].

The properties of the LJ, such as its shape and particle multiplicity, strongly depend on the unknown structure of the hidden sector and its couplings to the visible sector. Therefore the search criteria must be as model-independent as possible, targeting the basic experimental signatures that correspond to these objects. A mapping of the results of such a search onto a specific model can then follow.

After a brief description of the ATLAS detector in section 2, two simplified models of non-SM Higgs boson decays to LJs [6, 38] are presented in section 3. The LJ definition and search criteria are given in section 4. Section 5 deals with the LJ search in the data collected in 2012 and with the background evaluation. It is important to test the performance of these search criteria on some models predicting the production of final states containing LJs; the expected signal from the two models described in section 3 are presented in section 6. Systematic uncertainties are given in section 7. The final results of the search and their contribution to the parameter space exclusion plot for dark photons are presented in section 8. Section 9 summarizes the results.

## 2 The ATLAS detector

ATLAS is a multi-purpose detector [39] at the LHC, consisting of an inner tracking system (ID) contained in a superconducting solenoid, which provides a 2 T magnetic field parallel

to the beam direction, electromagnetic and hadronic calorimeters (EMCAL and HCAL) and a muon spectrometer (MS) that has a system of three large air-core toroid magnets.

The ID combines high-resolution detectors at the inner radii with continuous tracking elements at the outer radii. It provides measurements of charged particle momenta in the region of pseudorapidity  $|\eta| \leq 2.5$ .<sup>1</sup> The highest granularity is obtained around the vertex region using semiconductor pixel detectors arranged in three barrels at average radii of 5 cm, 9 cm, and 12 cm, and three disks on each side, between radii of 9 cm and 15 cm, followed by four layers of silicon microstrip detectors and by a transition radiation tracker. The electromagnetic and hadronic calorimeter system covers  $|\eta| \leq 4.9$  and, at  $\eta = 0$ , has a total depth of 9.7 interaction lengths (22 radiation lengths in the electromagnetic part). The MS provides trigger information ( $|\eta| \leq 2.4$ ) and momentum measurements ( $|\eta| \leq 2.7$ ) for charged particles entering the muon spectrometer. It consists of one barrel ( $|\eta| \leq 1.05$ ) and two endcaps ( $1.05 \leq |\eta| \leq 2.7$ ), each with 16 sectors in  $\phi$ , equipped with fast detectors for triggering and with chambers measuring the tracks of the outgoing muons with high spatial precision. The MS detectors are arranged in three stations at increasing distance from the IP: inner, middle and outer. Monitored drift tubes are used for precision tracking in the region  $|\eta| \leq 2.7$ , except for the innermost layer which uses cathode strip chambers in the interval  $2.0 \leq |\eta| \leq 2.7$ . The toroidal magnetic field allows for precise reconstruction of charged-particle tracks independent of the ID information.

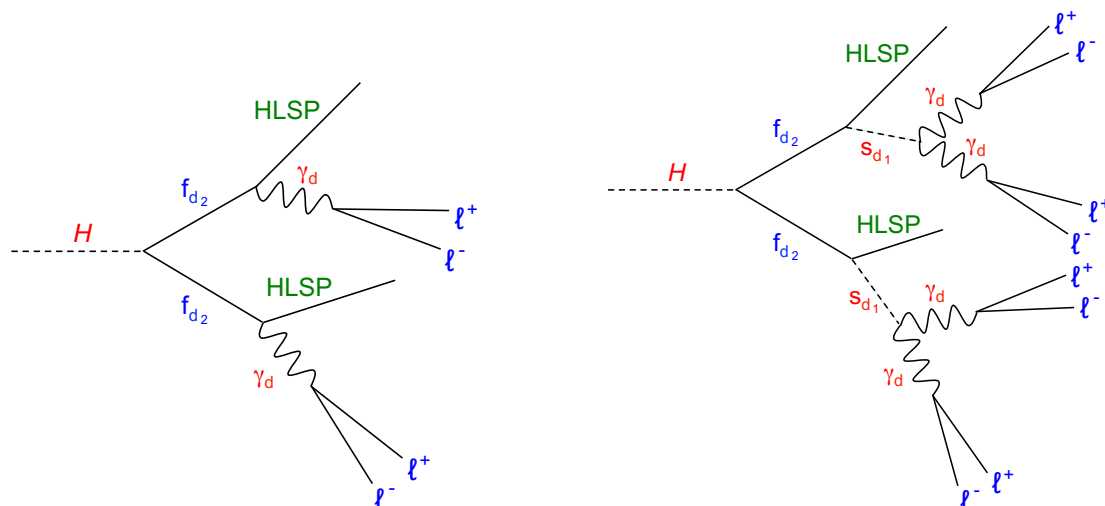
The trigger system has three levels [40] called Level-1 (L1), Level-2 (L2) and the Event Filter (EF). L1 is a hardware-based system using information from the calorimeter and MS. It defines one or more region-of-interest (RoIs), geometrical regions of the detector, identified by  $(\eta, \phi)$  coordinates, containing interesting physics objects. L2 and the EF (globally called the High-Level Trigger, HLT) are software-based systems and can access information from all sub-detectors. The three planes of MS trigger chambers (resistive plate chambers in the barrel and thin gap chambers in the endcaps) are located in the middle and outer (only in the barrel) stations. The L1 muon trigger requires hits in the middle stations to create a low transverse momentum ( $p_T$ ) muon RoI or hits in both the middle and outer stations for a high  $p_T$  muon RoI. The muon RoIs have a spatial extent of  $0.2 \times 0.2$  ( $\Delta\eta \times \Delta\phi$ ) in the barrel and of  $0.1 \times 0.1$  in the endcaps. L1 RoI information seeds the reconstruction of muon momenta by the HLT, which uses precision chamber information to obtain sharper trigger thresholds.

### 3 Lepton-jet models

It is important to evaluate the performance of the LJ search criteria by setting limits on models that predict LJs in the final state. Of particular relevance are models which predict non-SM Higgs boson decays to LJs. Indeed, the phenomenology of the Higgs boson

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<sup>1</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the  $z$ -axis coinciding with the beam pipe axis. The  $x$ -axis points from the interaction point to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .



**Figure 1.** Diagrams of the two FRVZ models used as benchmarks in the analysis.  $\ell^+ \ell^-$  corresponds to electron/muon/pion pair decay in the final state.

is extremely susceptible to new couplings, and new decay channels may thus easily exist. Since the structure of the unknown hidden sector may greatly influence the properties of the LJ, a simplified-model approach is highly beneficial. The two Falkowski-Ruderman-Volansky-Zupan (FRVZ) models [6, 38], which predict non-SM Higgs boson decays to LJs are considered. Figure 1 shows diagrams for the decay of the Higgs boson to LJs in the two models. The Higgs boson,  $H$ , decays to pairs of hidden fermions,  $f_{d2}$ . In the first model (left in figure 1)  $f_{d2}$  decays to a dark photon,  $\gamma_d$ , and to a lighter hidden fermion, HLSP (Hidden Lightest Stable Particle). In the second model (right in figure 1)  $f_{d2}$  decays to a HLSP and to a hidden scalar,  $s_{d1}$  that in turn decays to pairs of dark photons. For the  $\gamma_d$  decays, only electron, muon and pion final states are considered. In general, radiation in the hidden sector may occur, resulting in additional hidden photons. The number of such radiated photons, however, varies on an event-by-event basis and depends on unknown model-dependent parameters such as the hidden gauge coupling  $\alpha_d$ .<sup>2</sup> Therefore such a possibility is not considered here.

## 4 Lepton-jet search

There are a large number of possible LJ topologies resulting from different possible hidden sectors. For instance, the LJ shape is controlled, in part, by the typical boost of the hidden particles, which in turn is determined by the ratio of the decaying visible-sector particle's mass to the produced hidden-sector particle's mass. Additional dependence may arise from the strength of interactions within the hidden sector. For example, strong dynamics may result in broader jets such as those produced in QCD processes. Such dynamics further determines the multiplicity of particles within an LJ. Indeed, quite generally, hidden cascade decays and possible showering may result in very dense LJs.

<sup>2</sup>See equation (3.1) in ref. [41].

The search presented in this paper adopts a simplified approach with a generic definition of LJ in order to make the analysis as model-independent as possible. An LJ containing only one or two dark photons is considered in the optimization of the selection criteria but the search is also sensitive to more complex final states even if with lower detection efficiencies. Only displaced LJ from  $\gamma_d$  decay far from the interaction point are searched for.

In order to characterize the ATLAS detector response to different types of displaced LJs, an LJ gun Monte Carlo generator (MC) was developed. This MC generator is able to simulate non-prompt LJs produced by the decay of one  $\gamma_d$  or by the decay of a hidden scalar  $s_{d1}$  into two dark photons according to the model in ref. [6]. The branching ratio to electrons, muons and pions is also set according to ref. [6]. The  $\gamma_d$  lifetime is chosen so that a large fraction of the decays occur inside the sensitive ATLAS detector volume.<sup>3</sup>

Several LJ gun MC samples that span a wide range of the LJ parameter space were generated. These samples are used to evaluate a suitable set of LJ selection criteria and estimate the corresponding detection efficiency in ATLAS. For LJ with only one  $\gamma_d$  the  $\gamma_d$  masses of 0.05, 0.15, 0.4, 0.9 and 1.5 GeV were generated. For LJ with two dark photons the  $s_{d1}$  masses of 1, 2, 5 and 10 GeV are used. For each mass of the  $s_{d1}$ , only the subset of the  $\gamma_d$  masses kinematically allowed were generated. In order to cover a wide interval of possible LJ production kinematics, the  $p_T$  distributions of  $\gamma_d$  and  $s_{d1}$  were taken to be uniform in the range 10–100 GeV and the pseudorapidity was taken to be uniform in the range from  $-2.5$  to  $2.5$ . To study the detector response, the generated events were processed through the full ATLAS simulation chain based on GEANT4 [42, 43]. All MC samples are simulated with pile-up interactions included and re-weighted to match the conditions of the 2012 data sample.

#### 4.1 LJ definition

The MC studies of the detector's response to the LJs guide the characterization of the LJ and the identification of variables useful for the selection of the signal. At the detector level, a  $\gamma_d$  decaying to a muon pair is identified by two muons in the MS, while a  $\gamma_d$  decaying to an electron/pion pair is seen as one or two jets in the calorimeters. A cluster of only muons and no jets in a narrow cone is the signature of an LJ with all dark photons decaying to muon pairs. A cluster of two muons and one or two jets is typical of an LJ with one  $\gamma_d$  decaying into a muon pair and one  $\gamma_d$  decaying into an electron/pion pair. An LJ with one or two dark photons, both decaying to electron/pion pairs, results in one or more jets.

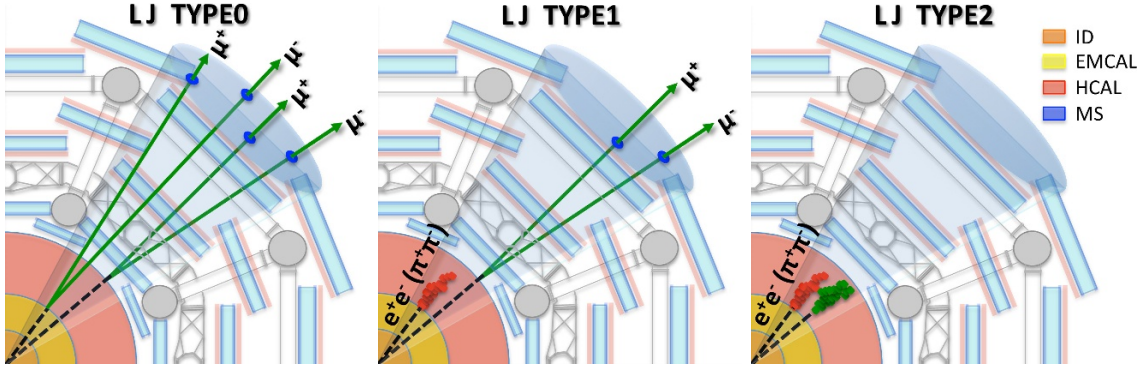
Muons from a  $\gamma_d$  decay beyond the last pixel detector layer are not matched with an ID track.<sup>4</sup> Therefore muon track reconstruction using only MS information (standalone muon, SA) has to be used. The search is limited to the pseudorapidity interval  $-2.5$  to  $2.5$  corresponding to the ID coverage.

An anti- $k_t$  calorimetric jet search algorithm [44, 45] with the radius parameter  $R = 0.4$ , is used to select  $\gamma_d$  decaying into an electron or pion pair. Jets must satisfy the

<sup>3</sup>The sensitive ATLAS detector volume is specified in section 6.1.

<sup>4</sup>The ID track reconstruction in ATLAS requires at least one hit in the pixel layers. Muon reconstruction requires a match between the muon track in the MS and an ID track (combined muons, CB).





**Figure 2.** Schematic picture of the LJ classification according to the  $\gamma_d$  decay final states: left TYPE0 LJ (only muons), centre TYPE1 LJ (muons and jets), right TYPE2 LJ (only jets). LJs containing only one  $\gamma_d$  contribute only to TYPE0 and TYPE2.

standard ATLAS quality selection criteria [46] with the cut  $p_T \geq 20$  GeV. The jet energy scale correction as defined in ref. [47] is applied. In the simulated LJ gun MC samples, LJs produced by one or two dark photons decaying to electron/pion pairs, are mostly reconstructed by the anti- $k_t$  algorithm as a single jet.

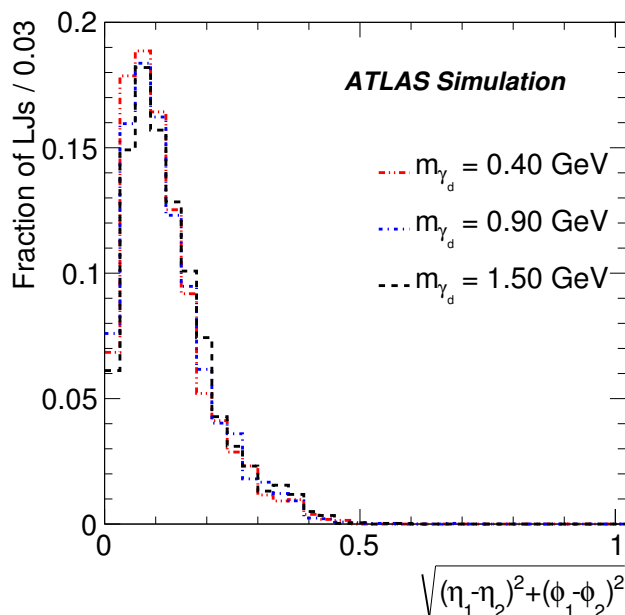
LJs are reconstructed using a simple clustering algorithm that combines all the muons and jets lying within a cone of fixed size in  $(\eta, \phi)$  space. The algorithm is seeded by the highest- $p_T$  muon. If at least two muons and no jets are found in the cone, the LJ is classified as TYPE0. Otherwise, if there are at least two muons and only one jet in the cone, the LJ found is of TYPE1. The search is then repeated with any unassociated muon until no muon seed is left. The remaining jets with electromagnetic (EM) fraction less than 0.4 and no muons in the cone are defined as TYPE2 LJ.<sup>5</sup> The LJ line of flight is obtained from the vector sum over all muon and jet momenta in the LJ. Figure 2 schematically shows the LJ classification according to the final state.

The size of the search cone for the various LJ types is optimized using the LJ gun MC samples. The cone size  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  around the LJ line of flight is chosen as the  $\Delta R$  that contains almost all the decay products (muons and jets) of the dark photons. Figure 3 shows the opening angle  $\sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$  between the two muons for  $\gamma_d \rightarrow \mu\mu$ , with both muons reconstructed in the MS, for the three  $\gamma_d$  masses. Figure 4 shows the maximum opening  $\sqrt{(\eta_i - \eta_k)^2 + (\phi_i - \phi_k)^2}$  between the reconstructed objects in the TYPE0 and TYPE1 LJs, produced by the decay of two  $\gamma_d \rightarrow \mu\mu$  or one  $\gamma_d \rightarrow \mu\mu$  and one  $\gamma_d \rightarrow ee/\pi\pi$ , for various masses of the hidden scalar and of the dark photon. All these distributions show that a  $\Delta R = 0.5$  is adequate to contain almost all the decay products. In summary the LJs are classified as:

- TYPE0 — to select LJs with all dark photons decaying to muons. This type selects  $\gamma_d$  decays beyond the pixel detector up to the first trigger plane of the MS.
- TYPE1 — to select LJs with one  $\gamma_d$  decaying to a muon pair and one  $\gamma_d$  decaying to an electron/pion pair. The range of decay distances targeted by TYPE1 LJ extends

<sup>5</sup>EM fraction is defined as the ratio of the energy deposited in the EMCAL to the total jet energy. From the LJ gun MC results,  $\gamma_d$  decaying inside the HCAL has EM fraction always below 0.4.





**Figure 3.** Opening  $\sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$  between the two muons in an LJ produced by the decay of a single  $\gamma_d$ , for the simulated  $\gamma_d$  mass states.

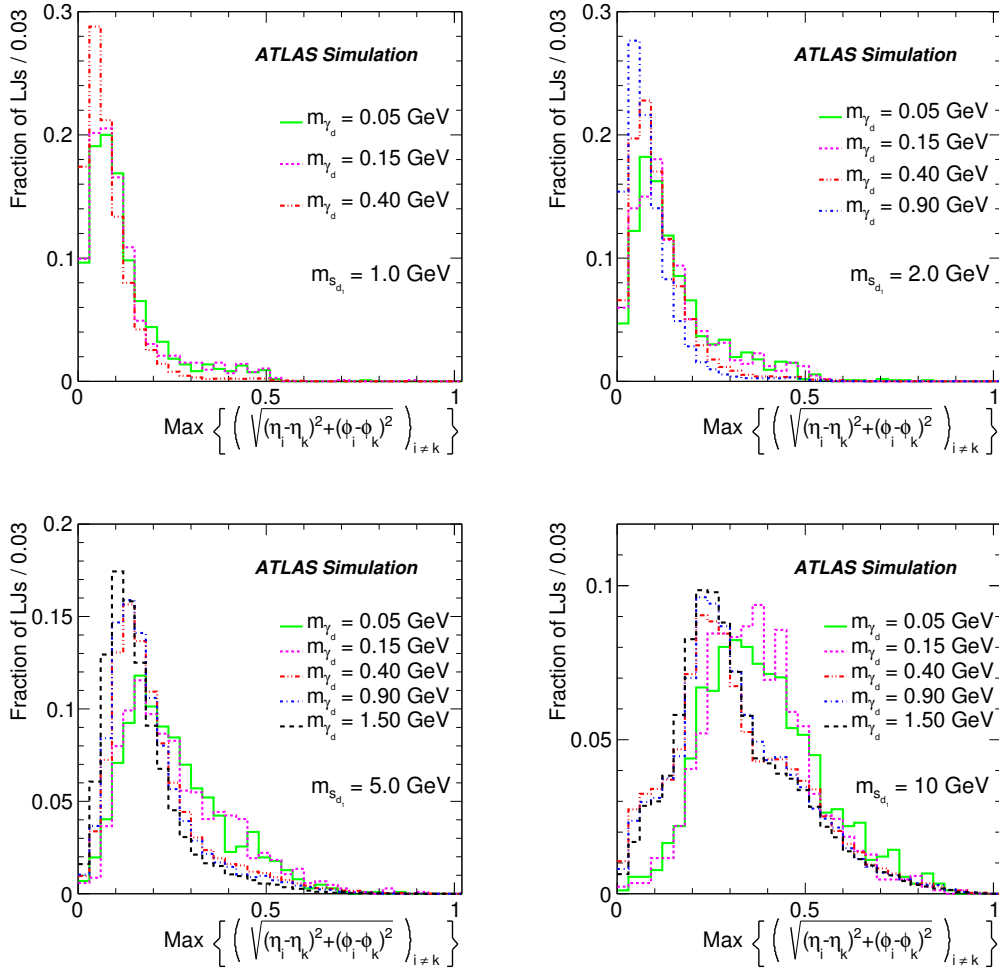
from the last ID pixel layer up to the end of the HCAL, for  $\gamma_d$  decaying into an electron/pion pair, and from the last ID pixel layer up to the first trigger plane of the MS, for the  $\gamma_d$  decays to muons.

- TYPE2 — to select LJs with all dark photons decaying to electron/pion pairs in the HCAL. The requirement of low EM fraction is necessary in order to reduce the overwhelming background due to SM multi-jet production.

The variables and the relative requirements useful for the background rejection of the individual LJ are discussed in section 4.2.

## 4.2 LJ selection and background rejection

The main sources of background to the LJ signal are multi-jet production and cosmic-ray muons that cross the detector in time coincidence with a bunch-crossing interaction. A sample of events collected in the empty bunch crossings is used to study the cosmic-ray background. To reduce contamination of LJ TYPE0 and TYPE1 by cosmic-ray muons, a requirement on the transverse and longitudinal impact parameters of the MS track at the primary vertex of  $|d_0| < 200$  mm and  $|z_0| < 270$  mm is used. The effect of these requirements on the  $\gamma_d \rightarrow \mu\mu$  decay was evaluated using the LJ gun MC of single  $\gamma_d$  (masses 0.4, 0.9 and 1.5 GeV), decaying to muon pairs beyond the last pixel layer. The expected signal is reduced by about 10–15% for decays in the ID, 15–25% for decays in the calorimeter system and 25–50% for decays in the MS, while the cosmic-ray background



**Figure 4.** Maximum opening  $\sqrt{(\eta_i - \eta_k)^2 + (\phi_i - \phi_k)^2}$  between the reconstructed objects in the LJ (muons for TYPE0 LJ, muons and jets for the TYPE1 LJ) for the  $s_{d1}$  masses 1 GeV (top left), 2 GeV (top right), 5 GeV (bottom left) and 10 GeV (bottom right) and for all the kinematically allowed  $\gamma_d$  masses.

is reduced by a factor of about 200. Since this search looks for non-prompt LJs, the requirement that muon tracks have no matched track in the ID (not-combined muons, NC) for TYPE0 and TYPE1 LJs removes about 80% of the background coming from processes with production of prompt and quasi-prompt muons.<sup>6</sup>

Energy deposits in the calorimeter due to cosmic-ray muons can be reconstructed as jets, creating a background to the TYPE1 and TYPE2 LJ selections. The variable used to remove jets from background cosmic-ray events is the timing, defined as the weighted mean time difference between  $t = 0$  (bunch-crossing time) and the time of energy deposition in the calorimeter cells. Rejecting jets with timing outside the interval between  $-1$  ns and  $5$  ns removes a large fraction of the cosmic-ray jets, with a very small loss of signal.

<sup>6</sup>The ID efficiency for prompt or quasi-prompt muons is greater than 99% [39].

The main background source for TYPE2 LJ is the production of multi-jet events. To study this background a control sample corresponding to the first 2 fb<sup>-1</sup> of the 2012 data is used. The events were selected by single-jet triggers with the lowest available thresholds of 15 GeV and 35 GeV. The LJ reconstruction algorithm is applied to this control sample. The requirement on the EM fraction and an additional requirement on the jet width were optimized by maximizing the signal significance (see eq. (97) of ref. [48]) defined as

$$\sqrt{2 \cdot ((s + b) \cdot \ln(1 + s/b) - s)}, \quad (4.1)$$

where  $s$  and  $b$  are the expected number of signal and background events, respectively.<sup>7</sup> The maximum significance for the EM fraction for TYPE2 LJ is obtained by requiring a jet EM fraction to be less than 0.1; this provides 99.9% multi-jet background rejection. A similar optimization leads to requiring a jet width less than 0.1 (80% multi-jet background rejection). In the transition regions between barrel and endcap calorimeters ( $1.0 < |\eta| < 1.4$ ), where there is a discontinuity in the EMCAL coverage, many jets exhibit a fake low EM fraction. Removal of jets with  $1.0 < |\eta| < 1.4$  rejects 30% of this type of background. An additional requirement of  $|\eta| < 2.5$  is also applied in order to have a jet coverage consistent with that of the ID.

Non-prompt LJs are expected to be highly isolated in the ID. Therefore the multi-jet background can be significantly reduced by requiring track isolation around the LJ direction in the ID. The track isolation variable  $\Sigma p_T$  (ID isolation) is defined as the sum of the transverse momenta of the tracks with  $p_T > 500$  MeV, reconstructed in the ID and matched to the primary vertex of the event, inside a cone of size  $\Delta R = 0.5$  around the direction of the LJ.<sup>8</sup> The primary interaction vertex is defined to be the vertex whose constituent tracks have the largest  $\Sigma p_T^2$ . Figure 5 shows the ID isolation distribution in the control sample of 2012 data selected by single-jet triggers. The ID isolation is validated with 2012 data using muons coming from a selected sample of  $Z \rightarrow \mu\mu$  decays.<sup>9</sup> The  $\Sigma p_T$  distribution obtained from the  $Z \rightarrow \mu\mu$  data sample agrees very well with the distribution obtained from the  $Z \rightarrow \mu\mu$  MC sample, as shown in figure 5. A  $\Sigma p_T \leq 3$  GeV requirement removes 97% of the multi-jet background while maintaining a very high LJ signal selection efficiency.

### 4.3 LJ reconstruction efficiency

In this section the LJ reconstruction efficiency using the LJ gun MC samples is presented. The reconstruction efficiency is given for LJ with only one  $\gamma_d$  as a function of the  $p_T$  and of the transverse decay distance  $L_{xy}$  of the  $\gamma_d$  at the generation level. The efficiency

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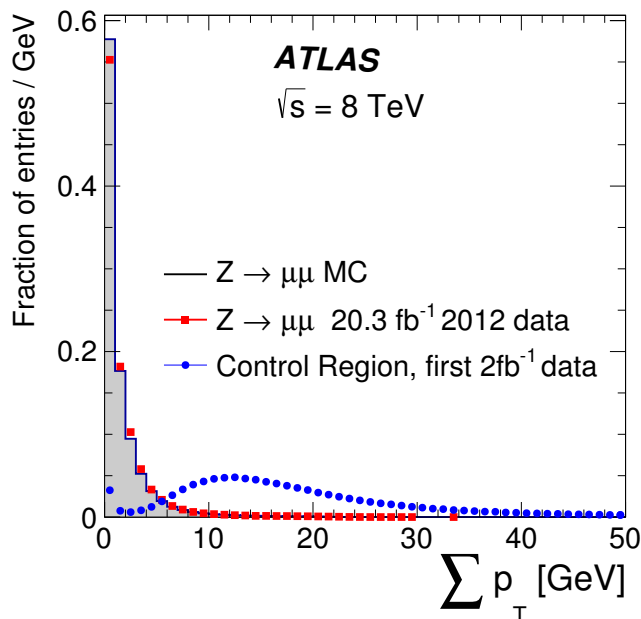
<sup>7</sup>The jet width  $W$  is defined as:

$$W = \frac{\sum_i \Delta R^i \cdot p_T^i}{\sum_i p_T^i}, \quad (4.2)$$

where  $\Delta R^i = \sqrt{(\Delta\phi_i)^2 + (\Delta\eta_i)^2}$  is the distance between the jet axis and the  $i^{th}$  jet constituent and  $p_T^i$  is the constituent  $p_T$  with respect to the beam axis.

<sup>8</sup>A requirement on the transverse and longitudinal impact parameters of the tracks at the primary vertex of  $|d_0| < 10$  mm and  $|z_0| < 10$  mm is used. The requirement of matching to the main primary interaction vertex helps in reducing the dependence of  $\Sigma p_T$  on the pile-up events.

<sup>9</sup>In this case the  $p_T$  of the ID track matched to the muon is removed from the  $\Sigma p_T$ .

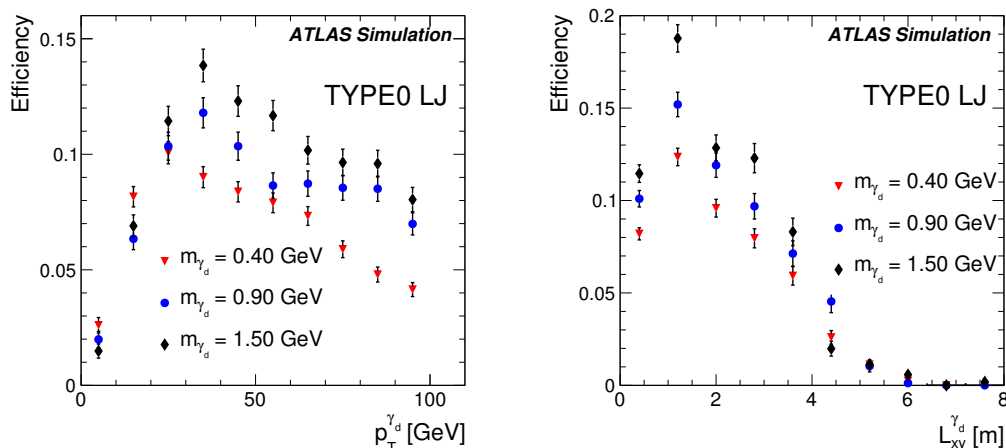


**Figure 5.** Distributions of  $\Sigma p_T$ : (filled dot) control sample of the first  $2\text{fb}^{-1}$  of 2012 data, (filled square)  $Z \rightarrow \mu\mu$  in 2012 data and (solid line)  $Z \rightarrow \mu\mu$  MC sample. All distributions are normalized to unit area.

is defined as the ratio of the number of reconstructed LJs of a given type, without any trigger requirement, to the corresponding number of generated ones, of the same type, in a given  $p_T$  or  $L_{xy}$  interval. For LJs with two dark photons, the reconstruction efficiency is presented as a function of the  $p_T$  of the  $s_{d1}$ . All the background rejection criteria defined in section 4.2 are applied to the reconstructed LJs.

Figure 6 shows the reconstruction efficiency for TYPE0 LJ as a function of the  $p_T$  (left) and  $L_{xy}$  (right) of the  $\gamma_d$  from LJ gun MC samples with  $\gamma_d$  masses 0.4, 0.9 and 1.5 GeV. LJ gun MC samples with only one  $\gamma_d$  ( $\gamma_d \rightarrow \mu\mu$ ) are used. As expected the efficiency decreases for  $p_T \leq 30\text{ GeV}$  due to one of the two muons of the decay losing all its energy inside the calorimeters and decreases at high values of  $p_T$  due to the smaller opening angle between the two muons. The efficiency also decreases with increasing distance  $L_{xy}$  from the primary vertex. This has two causes: the algorithm for reconstructing particle tracks in the MS has a loose requirement of extrapolation to the IP and the opening angle between the two muons decreases as the boost of the  $\gamma_d$  increases. The efficiency decrease at low  $L_{xy}$  is due to the isolation requirement, which rejects the LJ if the muon tracks are reconstructed in the ID.

Figure 7 shows the reconstruction efficiency for TYPE2 LJs as a function of the  $p_T$  (left) and  $L_{xy}$  (right) of the  $\gamma_d$  from LJ gun MC samples with  $\gamma_d$  masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. LJ gun MC samples with only one  $\gamma_d$  ( $\gamma_d \rightarrow ee/\pi\pi$ ) are used. As a consequence of the requirement on the EM fraction, mainly decays inside the HCAL are reconstructed. Figure 8 shows the reconstruction efficiency of TYPE0 LJs (top left), TYPE1 LJs (top



**Figure 6.** Reconstruction efficiency of TYPE0 LJs as a function of  $p_T$  (left) and  $L_{xy}$  (right) of the  $\gamma_d$  for  $\gamma_d \rightarrow \mu\mu$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

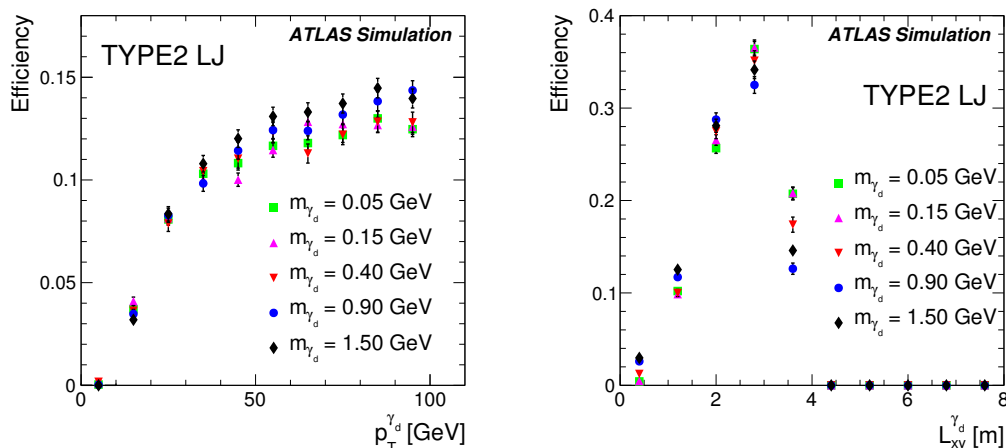
right) and TYPE2 LJs (bottom) as a function of the  $p_T$  of the  $s_{d1}$ , obtained from the LJ gun MC samples with an  $s_{d1}$  mass of 2 GeV and kinematically allowed  $\gamma_d$  masses. Only LJ gun MC samples with two dark photons in the final state are used. The efficiency distributions are compatible with those obtained from the single  $\gamma_d$  samples.<sup>10</sup>

#### 4.4 LJ trigger efficiency

The trigger efficiency for events containing two displaced LJs can be evaluated only at event level, i.e. taking into account the trigger response to both LJs. However LJ gun MC samples can provide information on the trigger efficiency for a single  $\gamma_d$ ; from this efficiency the trigger behaviour for the full event can be easily derived.

A large fraction of the ATLAS muon triggers are strictly linked to the primary vertex and therefore are very inefficient in selecting tracks arising from displaced decay vertices. Selection of displaced LJs of TYPE0 and TYPE1 needs an unprescaled multi-muon trigger that does not require matching between the muon track and an ID track and has a relatively low  $p_T$  threshold. The only available HLT trigger in 2012 data taking satisfying these specifications requires at least three reconstructed muons in the MS with  $p_T \geq 6$  GeV (3mu6 trigger). This multi-muon trigger requires, for an event containing two dark photons, one  $\gamma_d$  producing two RoIs and the other at least one. Therefore the efficiency of the trigger depends on the opening angle  $\Delta R$  between the two muons from the  $\gamma_d$  decay. If the opening angle is smaller than the trigger granularity (see section 2), the L1 selects only one RoI. Therefore the probability for a single  $\gamma_d$  to produce two distinct RoIs is needed in order to evaluate the trigger efficiency.

<sup>10</sup>In case of two dark photons in the same LJ, if one  $\gamma_d$  decays in electrons/pions before the HCAL, the LJ is rejected due to the low EM fraction requirement.



**Figure 7.** Reconstruction efficiency of TYPE2 LJs as a function of  $p_T$  (left) and  $L_{xy}$  (right) of the  $\gamma_d$  for  $\gamma_d \rightarrow ee/\pi\pi$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

Figure 9 shows the muon trigger efficiency,  $\varepsilon(2\text{mu}6)$ , for  $\gamma_d \rightarrow \mu\mu$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.4, 0.9 and 1.5 GeV, as a function of  $p_T$  (left) and  $\eta$  (right) of the  $\gamma_d$ . The efficiency  $\varepsilon(2\text{mu}6)$  is defined as the fraction of  $\gamma_d \rightarrow \mu\mu$  passing the offline selection that also satisfy the 2mu6 trigger. The decrease at high  $p_T$  reflects the loss of trigger efficiency in the MS barrel when the boost of the  $\gamma_d$  increases: the angular separation between the muons decreases reducing the probability of two distinct RoIs. The effect of higher trigger granularity in the endcap relative to the barrel is clearly visible in figure 9 (right).

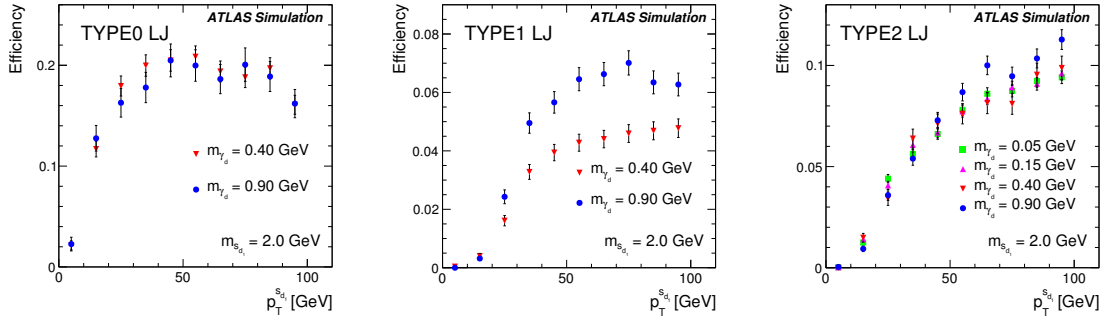
An estimate of the overall trigger efficiency per event,  $\varepsilon(3\text{mu}6)$ , can be derived from the  $\varepsilon(2\text{mu}6)$  obtained with the LJ gun MC samples. The probability of satisfying 3mu6 in events with two dark photons, is given by:

$$p^{3\text{mu}6} = 2 \cdot \varepsilon(1\text{mu}6) \cdot \varepsilon(2\text{mu}6) - \varepsilon(2\text{mu}6) \cdot \varepsilon(2\text{mu}6) \quad (4.3)$$

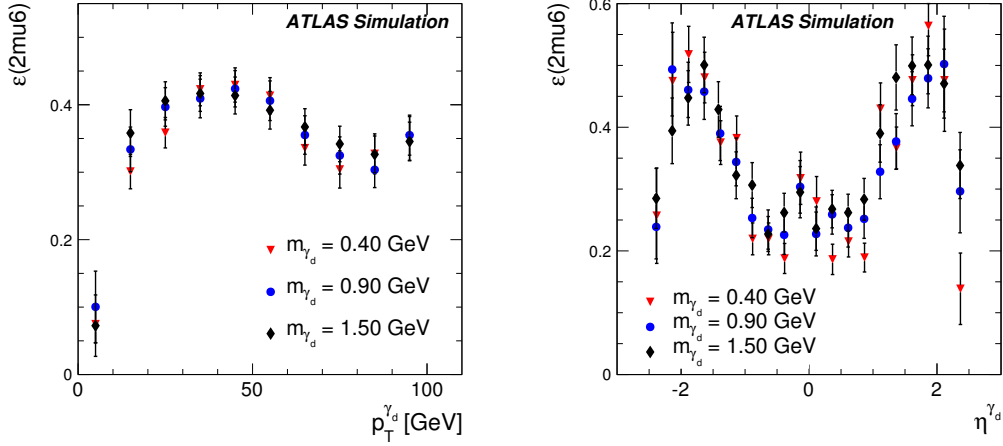
where  $\varepsilon(1\text{mu}6)$  and  $\varepsilon(2\text{mu}6)$  are the probabilities for a  $\gamma_d$  to generate a 1mu6 and 2mu6 trigger, respectively. The  $\varepsilon(1\text{mu}6)$  can be assumed to be the single-muon trigger efficiency (80% in the barrel and 90% in the endcap part of the muon spectrometer).

In order to select displaced TYPE2 LJs a single jet trigger with low EM fraction can be used [49]. The L1 trigger requires at least 40 GeV energy deposition in a narrow region  $0.1 \times 0.1$  ( $\Delta\eta \times \Delta\phi$ ) of the calorimeters. At L2 a cut  $\leq 0.06$  on the EM fraction of the jet is applied. In addition, the trigger requirements for the jets are:  $E_T > 30$  GeV,  $|\eta| \leq 2.5$  and no ID tracks with  $p_T > 1.0$  GeV in the region  $0.2 \times 0.2$  ( $\Delta\eta \times \Delta\phi$ ) around the jet axis. Finally, the EF requires the reconstructed jet to have  $E_T > 35$  GeV and applies beam-halo removal.<sup>11</sup>

<sup>11</sup>Uncalibrated calorimetric energy measurement is used in the three trigger levels.



**Figure 8.** Reconstruction efficiency of TYPE0 (top left), TYPE1 (top right) and TYPE2 (bottom) LJs as a function of the  $p_T$  of the  $s_{d1}$  for LJs with two dark photons for an  $s_{d1}$  mass of 2 GeV. For the  $\gamma_d$ , only the kinematically allowed masses are considered. The distributions for the other  $s_{d1}$  masses are very similar. The uncertainties are statistical only.

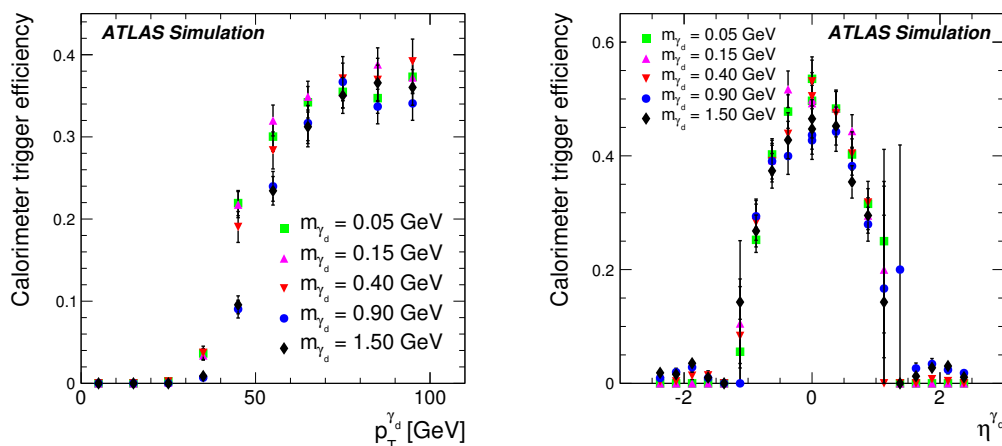


**Figure 9.** Muon trigger efficiency,  $\epsilon(2\mu6)$ , as a function of  $p_T$  (left) and  $\eta$  (right) of the  $\gamma_d$  for  $\gamma_d \rightarrow \mu\mu$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

Figure 10 shows the calorimetric trigger efficiency for  $\gamma_d \rightarrow ee/\pi\pi$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV as a function of  $p_T$  (left) and  $\eta$  (right) of the  $\gamma_d$ . This efficiency is defined as the fraction of  $\gamma_d \rightarrow ee/\pi\pi$  passing the offline selection that also satisfy the calorimetric trigger. The sharp decrease of the efficiency for  $p_T < 60$  GeV is due to the L1 trigger requirement  $E_T > 40$  GeV. The drop to zero for  $|\eta| > 1.0$  is due to the noisy-cell removal in the endcap hadronic calorimeter at trigger level [50].<sup>12</sup>

<sup>12</sup>A  $\gamma_d$  decay in the endcap HCAL is in general contained in a single cell. Most misreconstructed jets are caused by sporadic noise bursts in the endcap HCAL, where most of the energy is in single calorimeter cells, with often some cross-talk in neighbouring cells. Jets reconstructed from these problematic channels are considered fake jets and tagged as noise.





**Figure 10.** Calorimetric trigger efficiency as a function of  $p_T$  (left) and  $\eta$  (right) of the  $\gamma_d$  for  $\gamma_d \rightarrow ee/\pi\pi$  obtained from the LJ gun MC samples with  $\gamma_d$  masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. Similar distributions are obtained for LJs containing two dark photons. The uncertainties are statistical only.

## 5 Event selection and backgrounds

### 5.1 Data and background samples

The data used for this analysis were collected during the entire 2012 data-taking period and selected by the logical OR of the two triggers described in section 4.4. Only data in which all the ATLAS subdetectors were running at nominal conditions were selected. The total integrated luminosity corresponds to  $20.3 \text{ fb}^{-1}$ .

Potential backgrounds include all processes that lead to prompt muons with or without associated jets such as the SM processes  $W$ +jets,  $Z$ +jets,  $t\bar{t}$ , single-top,  $WW$ ,  $WZ$ , and  $ZZ$ . The MC samples used to estimate the prompt lepton background are generated using PYTHIA 8.165 [51] ( $W$ +jets and  $Z$ +jets) and MC@NLO 4.06 [52] ( $t\bar{t}$ ,  $WW$ ,  $WZ$ , and  $ZZ$ ). The generated MC events are processed through the full ATLAS simulation and reconstruction chain. Additional  $pp$  interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. All MC samples are re-weighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data.

Cosmic rays in ATLAS come mostly from the skyward direction and arrive mainly from the two large access shafts to the pit. Cosmic-ray muons interact with the detector as minimum-ionizing particles and most traverse the entire detector. In some cases, cosmic rays can produce large energy deposits in the calorimeter system. These may be reconstructed as jets, which result in a background to the TYPE1 and TYPE2 LJ selections used in this analysis. Moreover, muon bundles in cosmic-ray air showers can mimic the signature of TYPE0 LJs.<sup>13</sup> The same triggers used to select the data sample in the colli-

<sup>13</sup>Muon bundles are showers of high-multiplicity quasi-parallel penetrating particles produced by very high-energy cosmic rays.

| Requirement              | Description   |
|--------------------------|---|
| Two reconstructed LJs    | select events with at least two reconstructed LJs             |
| $\eta$ range (TYPE1)     | remove jets with $ \eta  > 2.5$                               |
| $\eta$ range (TYPE2)     | remove jets with $ \eta  > 2.5$ and $1.0 <  \eta  < 1.4$      |
| EM fraction (TYPE2)      | require EM fraction of the jet $< 0.1$                        |
| Jet width W (TYPE2)      | require width of the jet $< 0.1$                              |
| Jet timing (TYPE1/TYPE2) | require jets with timing $-1 \text{ ns} < t < 5 \text{ ns}$   |
| NC muons (TYPE0/TYPE1)   | require muons without ID track match                          |
| ID isolation             | require $\max\{\Sigma p_T\} \leq 3 \text{ GeV}$               |
| $\Delta\phi$             | require $ \Delta\phi  \geq 1 \text{ rad}$ between the two LJs |

**Table 1.** Requirements for selection of events with LJs. The requirements are applied to all LJ types unless otherwise specified.

sions were also active in the 2012 data taking in the empty bunch crossings. Such data are used to study and to estimate the cosmic-ray background to the signal.

## 5.2 Selection of events with LJs

The selection of events starts by requiring at least two reconstructed LJs (see section 4.1). The requirements for the individual LJ background rejection (see section 4.2) are then applied to the selected events. At the event level, additional requirements are made to separate the LJ signal from background.

**LJ isolation.** All the non-prompt LJs have to be isolated in the ID. As a global variable for the LJ event selection, the highest ID  $\Sigma p_T$  (see section 4.2) of the LJs in the event (denoted by  $\max\{\Sigma p_T\}$  in the following) is required to be  $\leq 3 \text{ GeV}$ .

**LJ production.** In order to reduce the background level in the LJ event selection, an additional requirement on the azimuthal angle  $\Delta\phi$  between the two LJs is introduced. A  $|\Delta\phi| \geq 1$  requirement significantly reduces the background without large signal losses even in models where LJ production is not back-to-back [41].

The complete list of the criteria for the selection of events with LJs is summarized in table 1 and the number of events observed in data applying the LJ selection is shown in table 2.

## 5.3 Background evaluation

**Cosmic-ray background.** The nominal LHC configuration for proton-proton collisions contains 3564 bunch crossings per revolution. Not all bunches are actually filled with protons. Empty bunch crossings contain no protons and allow for the study of cosmic-ray background events. The LJ selection for events triggered in the empty bunch crossings, using the same triggers as the ones used to select the data, is shown in table 3. The selection

| LJ pair types              | 0-0                 | 0-1  | 0-2   | 1-1  | 1-2   | 2-2   | All    |
|----------------------------|---------------------|------|-------|------|-------|-------|--------|
| Trigger selection          | $9.226 \times 10^6$ |      |       |      |       |       |        |
| Good primary vertex        | $9.212 \times 10^6$ |      |       |      |       |       |        |
| Two reconstructed LJs      | 946                 | 1771 | 16676 | 1382 | 19629 | 82653 | 123057 |
| $\eta$ range (TYPE1/TYPE2) | 946                 | 1269 | 5063  | 701  | 3838  | 25885 | 37702  |
| EM fraction (TYPE2)        | 946                 | 1269 | 393   | 701  | 172   | 4713  | 8194   |
| Jet width W (TYPE2)        | 946                 | 1269 | 350   | 701  | 148   | 3740  | 7154   |
| Jet timing (TYPE1/TYPE2)   | 946                 | 1054 | 216   | 547  | 92    | 578   | 3433   |
| NC muons (TYPE0/TYPE1)     | 27                  | 3    | 42    | 5    | 5     | 578   | 660    |
| ID isolation               | 12                  | 0    | 19    | 4    | 3     | 160   | 198    |
| $ \Delta\phi $             | 11                  | 0    | 11    | 4    | 3     | 90    | 119    |

**Table 2.** Number of selected data events at different stages of the selection process and for each of the LJ pair types, for the full 2012 data sample.

criteria used are identical to the ones employed for the filled bunch crossings, except for applying a primary vertex requirement. The ratio of filled to empty bunch crossings is used to rescale the observed number of events to the  $pp$  collision data. After rescaling, the estimated background contribution to the full 2012 dataset is  $40 \pm 10$ , as shown in the last row of table 3 where the quoted uncertainties are statistical only.

**Background from electroweak and  $t\bar{t}$  processes.** All these MC background samples give negligible contributions even at the trigger level.

**Multi-jet background using the ABCD method.** The multi-jet background evaluation is done using a data-driven (ABCD) method. This is a simplified matrix method that relies on the assumption that two relatively uncorrelated variables can be identified for the separation of signal from background. It is assumed that the multi-jet background distribution can be factorized in the  $|\Delta\phi|, \max\{\Sigma p_T\}$  plane. Figure 11 shows the event distribution in this plane before the requirements on  $|\Delta\phi|$  and  $\max\{\Sigma p_T\}$ . If A is the signal region ( $\max\{\Sigma p_T\} \leq 3 \text{ GeV}$  and  $|\Delta\phi| \geq 1$ ), the number of background events in A can be predicted from the population of the other three regions:  $N_A = N_D \times N_B/N_C$ , assuming a negligible leakage of signal into regions B, C and D. Table 4 summarizes the observed yields in the data for the three regions B, C and D. The cosmic-ray estimated values (using the cosmic-ray data collected in the empty bunches, rescaled for the filled-to-empty bunch ratio) in the same regions are given in the table; in this case the events in A are the expected ones from the cosmic-ray data, after rescaling. In order to evaluate the multi-jet background, the cosmic-ray contribution in region D is subtracted (cosmic rays are usually isolated); the estimated number of multi-jet background events in the signal region is  $N_A = 70 \pm 58(stat)$ . The expected multi-jet background in the signal region is strongly reduced by removing TYPE2-TYPE2 LJ pairs from the selection. Without this

| LJ pair types              | 0-0            | 0-1             | 0-2        | 1-1             | 1-2             | 2-2        | All         |
|----------------------------|----------------|-----------------|------------|-----------------|-----------------|------------|-------------|
| Trigger selection          | 161951         |                 |            |                 |                 |            |             |
| Good primary vertex        | not applicable |                 |            |                 |                 |            |             |
| Two reconstructed LJs      | 6              | 0               | 42         | 0               | 36              | 3744       | 3838        |
| $\eta$ range (TYPE1/TYPE2) | 6              | 0               | 29         | 0               | 17              | 2243       | 2295        |
| EM fraction (TYPE2)        | 6              | 0               | 29         | 0               | 17              | 2190       | 2242        |
| Jet width W (TYPE2)        | 6              | 0               | 22         | 0               | 6               | 1632       | 1666        |
| Jet timing (TYPE1/TYPE2)   | 6              | 0               | 6          | 0               | 0               | 24         | 36          |
| NC muons (TYPE0/TYPE1)     | 6              | 0               | 6          | 0               | 0               | 24         | 36          |
| ID isolation               | 6              | 0               | 6          | 0               | 0               | 24         | 36          |
| $ \Delta\phi $             | 6              | 0               | 5          | 0               | 0               | 4          | 15          |
| Rescaled to interactions   | $15 \pm 6$     | $0_{-0}^{+3.1}$ | $14 \pm 6$ | $0_{-0}^{+3.1}$ | $0_{-0}^{+3.1}$ | $11 \pm 7$ | $40 \pm 10$ |

**Table 3.** Result of applying the LJ selection to events triggered in the empty bunch crossings. Number of selected data events at different stages of the selection process and for each LJ pair types. Except for the last row, all these numbers are not rescaled by the ratio of filled to empty bunches in the LHC operation. The quoted uncertainties are statistical only.

| Data Type                     | Events in B  | Events in C | Events in D | Expected Events in A |
|-------------------------------|--------------|-------------|-------------|----------------------|
| Cosmic-ray data               | 0            | 0           | $60 \pm 13$ | $40 \pm 10$          |
| Data (cosmic rays subtracted) | $362 \pm 19$ | $99 \pm 10$ | $19 \pm 16$ | $70 \pm 58$          |

**Table 4.** Event yields in the four ABCD regions used to estimate the multi-jet background with the ABCD method in the LJ signal region. All LJ pair types are used. The quoted uncertainties are statistical only.

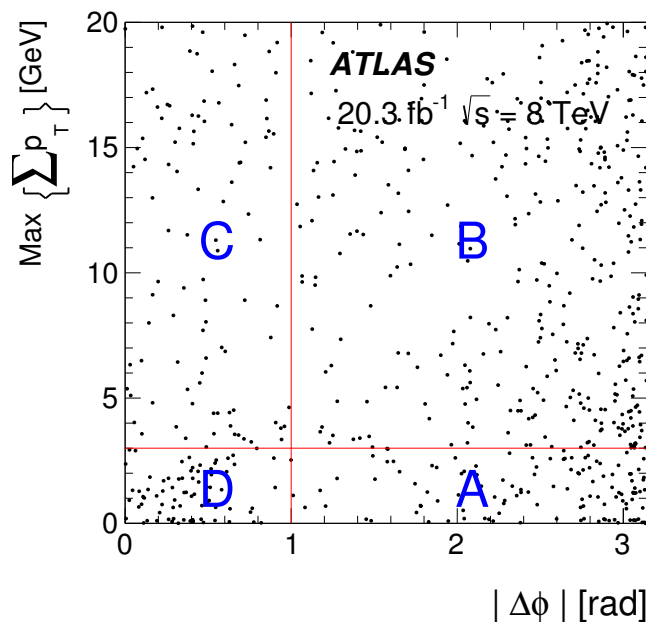
| Data Type                     | Events in B | Events in C | Events in D | Expected events in A |
|-------------------------------|-------------|-------------|-------------|----------------------|
| Cosmic-ray data               | 0           | 0           | $3 \pm 3$   | $29 \pm 9$           |
| Data (cosmic rays subtracted) | $29 \pm 5$  | $15 \pm 4$  | $6 \pm 4$   | $12 \pm 9$           |

**Table 5.** Event yields in the four regions used to estimate the multi-jet background with the ABCD method in the LJ signal region. TYPE2-TYPE2 LJs are excluded. The quoted uncertainties are statistical only.

LJ pair type, 29 events are observed in the signal region, corresponding to 24% of the total. The result of the background estimation obtained when removing TYPE2-TYPE2 is shown in table 5.

## 6 Results for the FRVZ models

In this section the data are interpreted in the context of the two FVRZ models as examples for the production of LJs.



**Figure 11.** Distribution of LJ events in the ABCD plane before the requirements  $\max\{\Sigma p_T\} \leq 3 \text{ GeV}$  and  $|\Delta\phi| \geq 1$ .

### 6.1 MC simulation of the FRVZ models

The set of parameters used to generate the signal MC samples is listed in table 6. The Higgs boson is generated through the gluon fusion production mechanism, which is the dominant production mechanism for a low-mass Higgs boson. The gluon fusion Higgs boson production cross section in  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$ , estimated at next-to-next-to-leading order (NNLO) [53], is  $\sigma_{\text{SM}} = 19.2 \text{ pb}$  for  $m_H = 125 \text{ GeV}$ . The masses of  $f_{d_2}$  and HLSP are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at  $m_{\text{HLSP}} + m_{\gamma_d} = m_{f_{d_2}}$ .<sup>14</sup>

For a dark photon mass of  $0.4 \text{ GeV}$ , the  $\gamma_d$  decay branching ratios (BR) are expected to be 45%  $e^+e^-$ , 45%  $\mu^+\mu^-$  and 10%  $\pi^+\pi^-$  [6]. The mean lifetime  $\tau$  of the  $\gamma_d$  (expressed as  $\tau$  times the speed of light  $c$ ) is a free parameter of the model. In the generated samples  $c\tau = 47 \text{ mm}$  is chosen so that about 85% of the decays occur inside the trigger-sensitive ATLAS detector volume, i.e. up to 7 m in radius and  $\pm 13 \text{ m}$  along the  $z$ -axis. The detection efficiency is estimated for a range of  $\gamma_d$  mean lifetimes through re-weighting of the generated samples.

The PYTHIA 8.165 generator is used, linked together with MadGraph5 [54] and BRIDGE [55], for gluon fusion production of the Higgs boson and the subsequent decay to hidden-sector particles. The generated MC events are processed through the full ATLAS simulation chain based on GEANT4 and then reconstructed.

<sup>14</sup>No hidden-sector radiation is included in the generated samples, which corresponds to the choice  $\alpha_d \lesssim 0.01$ . This may affect the trigger and reconstruction efficiencies.

| Model             | Events | $m_h$<br>[GeV] | $m_{f_{d2}}$<br>[GeV] | $m_{HLSP}$<br>[GeV] | $m_{sd1}$<br>[GeV] | $m_{\gamma_d}$<br>[GeV] | $c\tau_{\gamma_d}$<br>[mm] | BR<br>$\gamma_d \rightarrow ee$ | BR<br>$\gamma_d \rightarrow \mu\mu$ | BR<br>$\gamma_d \rightarrow \pi\pi$ |
|-------------------|--------|----------------|-----------------------|---------------------|--------------------|-------------------------|----------------------------|---------------------------------|-------------------------------------|-------------------------------------|
| Two dark photons  | 150k   | 125            | 5.0                   | 2.0                 | -                  | 0.4                     | 47                         | 0.45                            | 0.45                                | 0.10                                |
| Four dark photons | 150k   | 125            | 5.0                   | 2.0                 | 2.0                | 0.4                     | 47                         | 0.45                            | 0.45                                | 0.10                                |

**Table 6.** Parameters of the FRVZ models used to generate the signal MC samples.

| LJ pair types              | 0-0             | 0-1       | 0-2        | 1-1             | 1-2             | 2-2        | All         |
|----------------------------|-----------------|-----------|------------|-----------------|-----------------|------------|-------------|
| Total number of events     | $39730 \pm 100$ |           |            |                 |                 |            |             |
| Trigger selection          | $1330 \pm 30$   |           |            |                 |                 |            |             |
| Good primary vertex        | $1330 \pm 30$   |           |            |                 |                 |            |             |
| Two reconstructed LJs      | 86              | 9         | 40         | 0               | 1               | 39         | $175 \pm 7$ |
| $\eta$ range (TYPE1/TYPE2) | 86              | 8         | 27         | 0               | 1               | 23         | $145 \pm 6$ |
| EM fraction (TYPE2)        | 86              | 8         | 23         | 0               | 1               | 12         | $130 \pm 6$ |
| Jet width W (TYPE2)        | 86              | 8         | 23         | 0               | 1               | 12         | $130 \pm 6$ |
| Jet timing (TYPE1/TYPE2)   | 86              | 6         | 23         | 0               | 1               | 11         | $128 \pm 6$ |
| NC muons (TYPE0/TYPE1)     | 50              | 4         | 17         | 0               | 0               | 11         | $82 \pm 5$  |
| ID isolation               | 37              | 2         | 13         | 0               | 0               | 10         | $63 \pm 4$  |
| $ \Delta\phi $             | $35 \pm 3$      | $2 \pm 1$ | $12 \pm 2$ | $0_{-0}^{+0.6}$ | $0_{-0}^{+0.6}$ | $10 \pm 2$ | $60 \pm 4$  |

**Table 7.** Expected number of LJ events for the two- $\gamma_d$  FRVZ model, using the parameter values in table 6. The numbers refer to selected signal events at different stages of the selection process and for each LJ pair type. The number of signal events is rescaled to the  $20.3 \text{ fb}^{-1}$  total integrated luminosity and the quoted uncertainties are statistical only. The detection efficiency is  $1.5 \times 10^{-3}$ .

## 6.2 LJ selection applied to FRVZ models

Assuming a 10% BR of the Higgs boson to the hidden sector and a total integrated luminosity of  $20.3 \text{ fb}^{-1}$ , the expected number of LJ events for the two benchmark models are shown in table 7 and table 8. Signals of  $60 \pm 7$  (stat) and  $104 \pm 9$  (stat) events are expected for the two- $\gamma_d$  and four- $\gamma_d$  FRVZ models, respectively.

## 7 Systematic uncertainties

The following effects are considered as possible sources of systematic uncertainty and are included as input to obtain, using the *CLs* method [56], the upper limits on the  $\sigma \times \text{BR}$  for the processes  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$  of the FRVZ models.

- **Luminosity**

The overall normalization uncertainty of the integrated luminosity is 2.8%. The systematic uncertainty on the luminosity is derived following the same methodology as that detailed in ref. [57].

| LJ pair types              | 0-0             | 0-1        | 0-2       | 1-1       | 1-2       | 2-2             | All          |
|----------------------------|-----------------|------------|-----------|-----------|-----------|-----------------|--------------|
| Total number of events     | $39730 \pm 100$ |            |           |           |           |                 |              |
| Trigger selection          | $2518 \pm 42$   |            |           |           |           |                 |              |
| Good primary vertex        | $2518 \pm 42$   |            |           |           |           |                 |              |
| Two reconstructed LJs      | 196             | 121        | 71        | 23        | 24        | 14              | $448 \pm 11$ |
| $\eta$ range (TYPE1/TYPE2) | 196             | 83         | 32        | 13        | 9         | 5               | $337 \pm 10$ |
| EM fraction (TYPE2)        | 196             | 83         | 11        | 13        | 6         | 1               | $308 \pm 9$  |
| Jet width W (TYPE2)        | 196             | 83         | 11        | 13        | 6         | 1               | $308 \pm 9$  |
| Jet timing (TYPE1/TYPE2)   | 196             | 80         | 11        | 11        | 5         | 1               | $304 \pm 9$  |
| NC muons (TYPE0/TYPE1)     | 101             | 39         | 8         | 5         | 4         | 1               | $158 \pm 6$  |
| ID isolation               | 72              | 24         | 6         | 3         | 2         | 1               | $107 \pm 5$  |
| $ \Delta\phi $             | $70 \pm 4$      | $23 \pm 2$ | $5 \pm 1$ | $3 \pm 1$ | $2 \pm 1$ | $0_{-0}^{+0.6}$ | $104 \pm 5$  |

**Table 8.** Expected number of LJ events for the four- $\gamma_d$  FRVZ model, using the parameter values in table 6. The numbers refer to selected signal events at different stages of the selection process and for each LJ pair type. The number of signal events is rescaled to the  $20.3 \text{ fb}^{-1}$  total integrated luminosity and the quoted uncertainties are statistical only. The detection efficiency is  $2.6 \times 10^{-3}$ .

- **Higgs production cross section**

The uncertainty on the Higgs boson gluon fusion production cross section at  $\sqrt{s} = 8 \text{ TeV}$  is 8% [53].

- **Trigger**

The systematic uncertainty on the 3mu6 trigger efficiency was assumed to be dominated by the systematic on the 2mu6 trigger. The systematic uncertainty on the 2mu6 trigger efficiency was evaluated using a tag-and-probe method applied to  $J/\psi \rightarrow \mu\mu$  2012 data and MC samples; it amounts to 5.8%. The systematic uncertainty on the calorimetric trigger was evaluated for each requirement at L2 [58]; the largest uncertainty, coming from the low EM fraction requirement, is 11%.

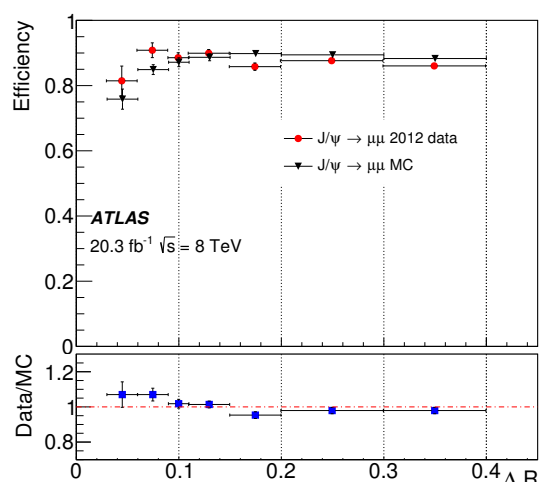
- **Muon reconstruction efficiency**

The systematic uncertainty on the single  $\gamma_d$  reconstruction efficiency is evaluated using the tag-and-probe method applied to  $J/\psi \rightarrow \mu\mu$  2012 data and MC samples. The  $J/\psi \rightarrow \mu^+\mu^-$  decays were selected and the efficiency evaluated as a function of the opening angle  $\Delta R$  between the two muons, both for data and for  $J/\psi$  MC events (figure 12 (top)). The two measures differ by less than two standard deviations at each point as shown in figure 12 (bottom). For low  $\Delta R$  values the efficiency decreases because it is more difficult for the MS tracking algorithms to reconstruct two tracks with small angular separation. The resulting systematic uncertainty is 5.4%.

- **Muon momentum resolution**

The systematic uncertainty on the muon momentum resolution for NC muons was evaluated by smearing and shifting the momentum of the muons by scale factors





**Figure 12.** Reconstruction efficiency of single NC muon with the tag-and-probe method as a function of  $\Delta R$  between the two muons in data and the  $J/\psi \rightarrow \mu^+\mu^-$  MC sample (top), and the corresponding ratio of these two efficiencies (bottom).

derived from comparison of  $Z \rightarrow \mu\mu$  decays in data and MC simulation, and by observing the effect of this shift on the signal efficiency. The overall effect of the muon momentum resolution uncertainty is negligible.

- **Jet energy scale (JES)**

The effect of the JES uncertainty components [59] was evaluated for the jets of the TYPE1 and TYPE2 LJs. This uncertainty was applied to the MC signal samples. The variation in event yield amounts to 0.9% and to 1.7% for the two- $\gamma_d$  and four- $\gamma_d$  samples, respectively.

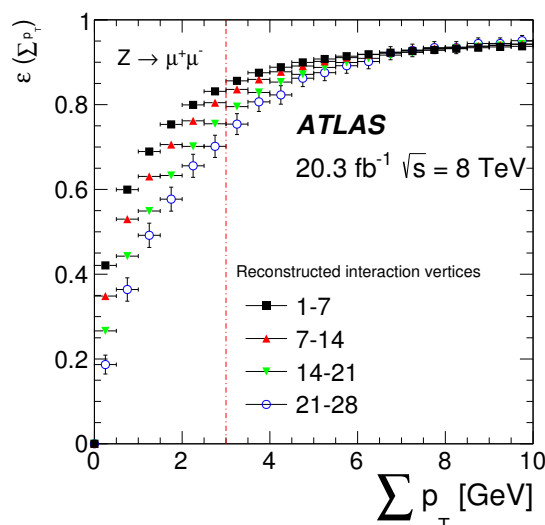
- **Effect of pile-up on  $\Sigma p_T$**

The presence of multiple collisions per bunch crossing (pile-up) affects the efficiency of the ID isolation criterion defined by the  $\Sigma p_T$  variable. The systematic uncertainty on the  $\Sigma p_T$  isolation efficiency due to pile-up is evaluated by computing the isolation efficiency  $\varepsilon(\Sigma p_T)$  for muons from a sample of reconstructed  $Z \rightarrow \mu\mu$  in data, as a function of the number of interaction vertices in the event.<sup>15</sup> The distributions of the isolation efficiency as a function of the isolation variable, for four subsamples of events with an increasing number of interaction vertices are shown in figure 13. The effect of pile-up on the isolation efficiency is quantified by assuming for it the uniform distribution (worst case). The corresponding variance computed at  $\Sigma p_T = 3$  GeV was assumed as systematic uncertainty. It amounts to 4.1%.

- **Multi-jet background estimation**

The systematic uncertainties that can affect the multi-jet background evaluation are related to the data-driven method used. The limits used to define the various

<sup>15</sup>The  $\varepsilon(\Sigma p_T)$  efficiency is defined as the number of muons with  $\Sigma p_T$  not exceeding a given value, divided by the total number of muons. The ID track matched with the muon is removed from the sum.



**Figure 13.** Isolation efficiency as a function of  $\Sigma p_T$  for four intervals of the number of reconstructed interaction vertices per event in a  $Z \rightarrow \mu\mu$  data sample.

regions were changed to take into account the expected uncertainty on  $|\Delta\phi|$  (comparing the LJ direction at the MC generator level with the reconstructed direction,  $\sigma_{|\Delta\phi|} = 0.1$  rad) and on  $\Sigma p_T$  (from the isolation distribution using the  $Z \rightarrow \mu\mu$  data sample,  $\sigma_{\Sigma p_T} = 0.6$  GeV). The background values were recomputed. This systematic uncertainty amounts to 15%. The additional effect of signal leakage into the control regions is taken into account by the simultaneous ABCD method used (see section 8).

- **Cosmic-ray background**

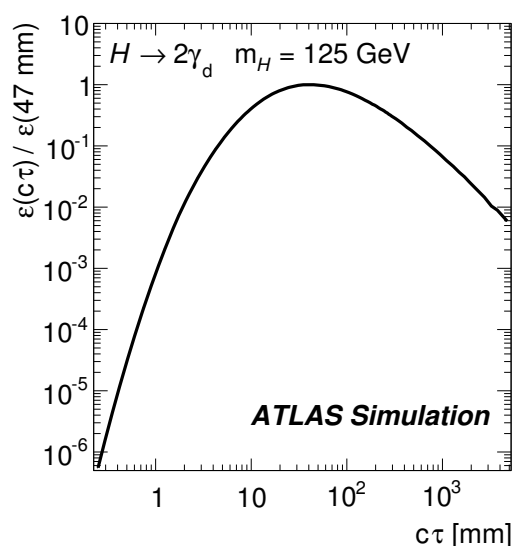
The systematic uncertainty on the cosmic-ray background is taken to be the statistical uncertainty on the number of cosmic-ray events in region D of the ABCD matrix (see table 4 and 5). The overall uncertainty is 22%. Excluding the TYPE2-TYPE2 events it is 100%.

- **$\gamma_d$  detection efficiency and  $p_T$  resolution**

Two additional effects were considered: the statistical uncertainty on the detection efficiency as a function of the decay position of the  $\gamma_d$  (see figures 6 and 7) and the resolution effects on the  $p_T$  of the  $\gamma_d$ . The reconstructed  $p_T$  of the  $\gamma_d$  differs from the MC generator-level  $p_T$  value, inducing a 10% uncertainty.

## 8 Results and interpretation

Table 9 summarizes the data and background results of the search for LJs in the 2012 data sample. Both for all LJ pair events and for the case where the TYPE2-TYPE2 LJs are excluded the data agree with the background expectation.

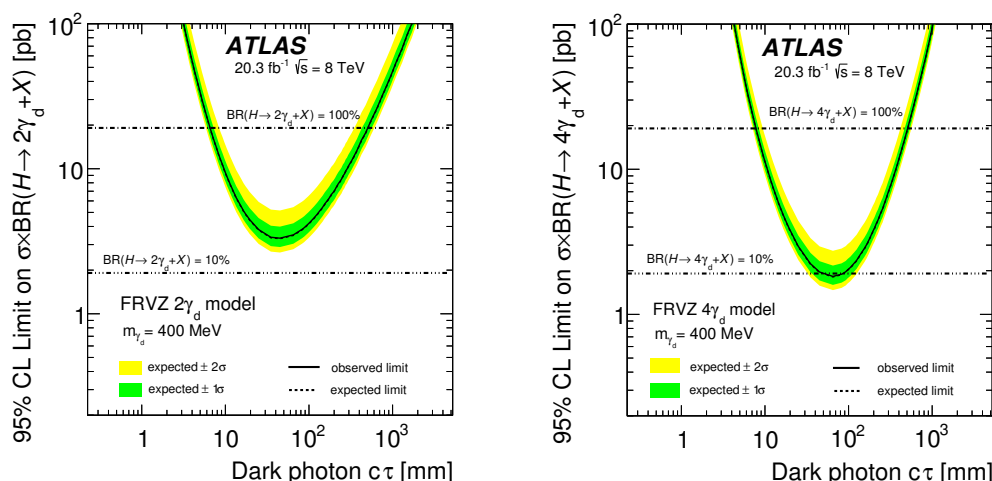


**Figure 14.** Ratio of the integrated detection efficiency at a given  $c\tau$  to the detection efficiency at  $c\tau = 47$  mm of the reference  $H \rightarrow 2\gamma_d + X$  MC sample.

|                   | All LJ pair types   | TYPE2-TYPE2 LJs excluded |
|-------------------|---------------------|--------------------------|
| Data              | 119                 | 29                       |
| Cosmic rays       | $40 \pm 11 \pm 9$   | $29 \pm 9 \pm 29$        |
| Multi-jets (ABCD) | $70 \pm 58 \pm 11$  | $12 \pm 9 \pm 2$         |
| Total background  | $110 \pm 59 \pm 14$ | $41 \pm 12 \pm 29$       |

**Table 9.** Summary of the LJ selection applied to data and background in the full 2012 data sample. The first uncertainty is statistical, while the second is systematic.

The results of the search for LJ production are used to set upper limits on the Higgs boson decay branching fraction to LJs as a function of the  $\gamma_d$  mean lifetime, according to the FRVZ models. The efficiency of the selection criteria described above is evaluated for the simulated FRVZ model samples as a function of the mean lifetime of the  $\gamma_d$ . The signal MC events are weighted by the detection probability of the  $\gamma_d$  in the various regions of the detector, generating their decay points according to a chosen value of the  $\gamma_d$  proper decay length ( $c\tau$  times the  $\gamma_d$  Lorentz factor), with  $c\tau$  ranging from 0.5 to 4750 mm. The number of selected events are then rescaled by the ratio of the integrated detection efficiency at a given  $c\tau$ ,  $\varepsilon(c\tau)$ , to the efficiency for the reference sample,  $\varepsilon(47 \text{ mm})$  (see table 7 and 8). Figure 14 shows, for the  $H \rightarrow 2\gamma_d + X$  model, the ratio  $\varepsilon(c\tau)/\varepsilon(47 \text{ mm})$  as a function of  $c\tau$ . These numbers, together with the expected number of background events (multi-jets and cosmic rays), are used as input to obtain limits at the 95% confidence level (CL) on the cross section times branching ratio ( $\sigma \times \text{BR}$ ) for the processes  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$ . The simultaneous *CLs* method is used to determine the limits, where the ABCD regions are populated from the data-driven background estimate and from the

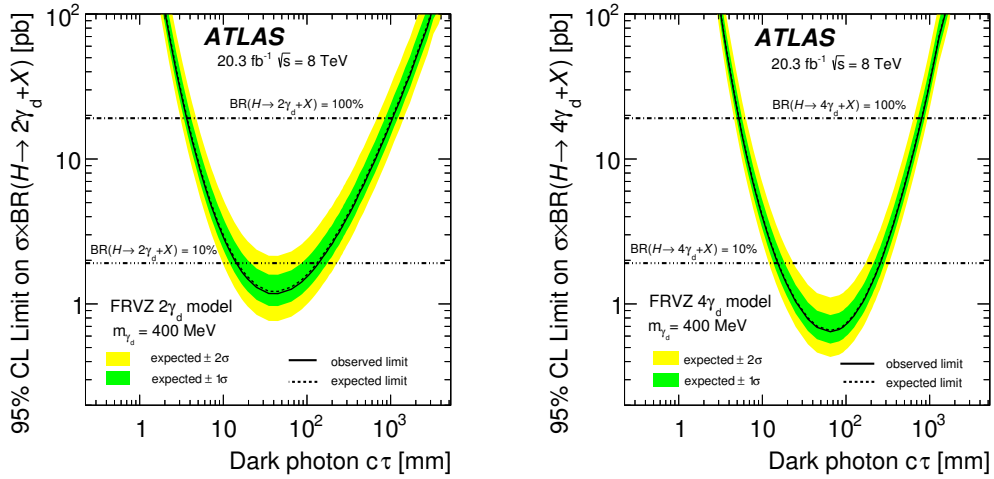


**Figure 15.** The 95% upper limits on the  $\sigma \times \text{BR}$  for the processes  $H \rightarrow 2\gamma_d + X$  (left) and  $H \rightarrow 4\gamma_d + X$  (right), as a function of the  $\gamma_d$  lifetime ( $c\tau$ ) for the FRVZ benchmark samples. The expected limit is shown as the dashed curve and the almost identical solid curve shows the observed limit. The horizontal lines correspond to  $\sigma \times \text{BR}$  for two values of the BR of the Higgs boson decay to dark photons.

appropriate signal hypothesis. It also takes into account contaminations from sources of background other than QCD processes.

All the systematic uncertainties discussed in section 7, except the ones on the signal MC cross sections, and their correlations are taken into account in calculating the limits. As a final cross-check the number of expected multi-jet background events in the signal region from the simultaneous  $CL_s$  ABCD method, can be compared with the expected background from the ABCD method assuming no signal (see section 5.3). For the two- $\gamma_d$  model the estimated background is  $13 \pm 8$  events and for the four- $\gamma_d$  model it is  $13 \pm 7$  events, to be compared with  $12 \pm 9$  events obtained by ABCD method assuming no signal (section 5.3). The resulting exclusion limits on the  $\sigma \times \text{BR}$ , assuming the Higgs boson SM gluon fusion production cross section  $\sigma_{\text{SM}} = 19.2$  pb, are shown in figure 15 as a function of the  $\gamma_d$  mean lifetime (expressed as  $c\tau$ ) for the two models. The exclusion plots with the TYPE2-TYPE2 category of events removed are shown in figure 16. In figure 15 and figure 16 the observed limit is slightly better than the expected one, because the number of events in the signal region is slightly smaller than the expected background from cosmic rays and multi-jets. It is seen that for these two models the search is more sensitive when excluding the TYPE2-TYPE2 events. Table 10 shows the ranges in which the  $\gamma_d$  lifetime ( $c\tau$ ) is excluded at the 95% CL for  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$  assuming a BR of 10%. The corresponding limits with TYPE2-TYPE2 events excluded are shown in table 11.

For the case of a hidden photon which kinetically mixes with the SM photon, these limits can be converted into exclusion limits on the kinetic mixing parameter  $\epsilon$  using the eqs. (4) and (5) of ref. [9]. For more details see also refs. [2, 6]. For  $H \rightarrow 2\gamma_d + X$  with a  $\gamma_d$  mass = 0.4 GeV excluding TYPE2-TYPE2 events, the interval that is excluded at 95% CL is  $7.7 \times 10^{-7} \leq \epsilon \leq 2.7 \times 10^{-6}$ .



**Figure 16.** The 95% upper limits on the  $\sigma \times \text{BR}$  for the processes  $H \rightarrow 2\gamma_d + X$  (left) and  $H \rightarrow 4\gamma_d + X$  (right), as a function of the  $\gamma_d$  lifetime ( $c\tau$ ) for the FRVZ benchmark samples, excluding the TYPE2-TYPE2 events. The expected limit is shown as the dashed curve and the almost identical solid curve shows the observed limit. The horizontal lines correspond to  $\sigma \times \text{BR}$  for two values of the BR of the Higgs boson decay to dark photons.

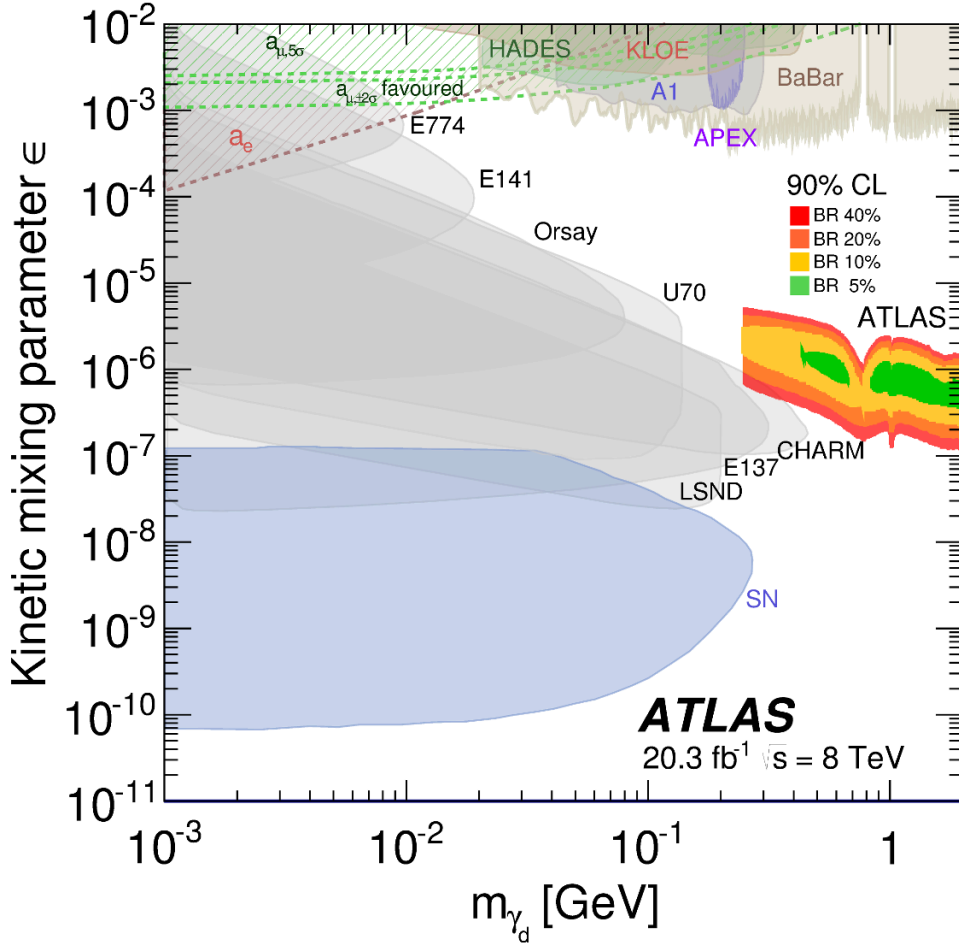
| FRVZ model                    | Excluded $c\tau$ [mm]<br>BR(10%) |
|-------------------------------|----------------------------------|
| $H \rightarrow 2\gamma_d + X$ | no limit                         |
| $H \rightarrow 4\gamma_d + X$ | $52 \leq c\tau \leq 85$          |

**Table 10.** Ranges of  $\gamma_d$  lifetime ( $c\tau$ ) excluded at 95% CL for  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$ , assuming 10% BR and the Higgs boson SM gluon fusion production cross section and including the TYPE2-TYPE2 events.

| FRVZ model                    | Excluded $c\tau$ [mm]<br>BR(10%) |
|-------------------------------|----------------------------------|
| $H \rightarrow 2\gamma_d + X$ | $14 \leq c\tau \leq 140$         |
| $H \rightarrow 4\gamma_d + X$ | $15 \leq c\tau \leq 260$         |

**Table 11.** Ranges of  $\gamma_d$  lifetime ( $c\tau$ ) excluded at 95% CL for  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$ , assuming 10% BR and the Higgs boson SM gluon fusion production cross section. TYPE2-TYPE2 events are not used.

These results are also interpreted in the context of the Vector portal model as exclusion contours in the kinetic mixing parameter  $\epsilon$  vs  $\gamma_d$  mass plane [17, 27, 60] as shown in figure 17. Assuming Higgs decay branching fractions into  $\gamma_d$  of 5/10/20/40% and the NNLO gluon fusion Higgs production cross section, the lifetime limits can be converted into kinetic mixing parameter  $\epsilon$  limits. While the other limits are model-independent because they produce the hidden photon through the vector portal coupling, this limit



**Figure 17.** Parameter space exclusion plot for dark photons as a function of the  $\gamma_d$  mass and of the kinetic mixing parameter  $\epsilon$  from figure 6 of ref. [60]. Shown are existing 90% CL exclusion regions from beam dump experiments E137, E141, and E774 [16–18], Orsay [23], U70 [24], CHARM [25], LSND [26], A1 [20], the electron and muon anomalous magnetic moment [33–35], HADES [30], KLOE [28, 29], the test run results reported by APEX [19], an estimate using a BaBar result [22, 31, 32], and constraints from astrophysical observations [36, 37]. The 90% CL exclusion limits from the present search, assuming the FRVZ model  $H \rightarrow 2\gamma_d + X$  with decay branching fraction to  $\gamma_d$  of 5/10/20/40% and the NNLO gluon fusion Higgs production cross section, are shown.

does depend on the additional assumption on the Higgs branching fraction to the hidden sector. The resulting 90% CL exclusion regions for  $H \rightarrow 2\gamma_d + X$  are shown in figure 17; the  $\gamma_d$  mass interval (0.25–1.5) GeV corresponds to the values in which the  $\gamma_d$  decay branching fractions and the detection efficiencies are comparable with those for the 0.4 GeV  $\gamma_d$  mass. The systematic uncertainties due to the detection efficiency and decay branching fraction variations as a function of the  $\gamma_d$  mass were estimated and included in the 90% CL exclusion region evaluations.

## 9 Conclusions

The ATLAS detector at the LHC is used to search for the production of non-prompt LJs in a  $20.3\text{ fb}^{-1}$  sample of  $\sqrt{s} = 8\text{ TeV}$   $pp$  collisions. Starting from a quite general definition of non-prompt LJs, a set of selection criteria able to isolate their signature from the SM and cosmic-rays backgrounds were defined. The observed data are consistent with the experimental background expectations. This result can be used to set upper limits on non-SM Higgs boson decays to LJs according to the FRVZ models. Limits are set on the  $\sigma \times \text{BR}$  for  $H \rightarrow 2\gamma_d + X$  and  $H \rightarrow 4\gamma_d + X$  for  $m_H = 125\text{ GeV}$  and a  $\gamma_d$  mass of  $0.4\text{ GeV}$ , as a function of the long-lived particle mean lifetime. Assuming the SM gluon fusion production cross section for a  $125\text{ GeV}$  Higgs boson, its BR to hidden-sector photons is found to be below 10%, at 95% CL, for hidden photon  $c\tau$  in the range  $14\text{ mm} \leq c\tau \leq 140\text{ mm}$  for the  $H \rightarrow 2\gamma_d + X$  model and in the range  $15\text{ mm} \leq c\tau \leq 260\text{ mm}$  for the  $H \rightarrow 4\gamma_d + X$  model.

These results are also interpreted in the context of the Vector portal model as exclusion contours in the kinetic mixing parameter  $\epsilon$  vs  $\gamma_d$  mass plane and significantly improve the constraints from other experiments.

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B. Cole<sup>35</sup>, S. Cole<sup>108</sup>, A.P. Colijn<sup>107</sup>, J. Collot<sup>55</sup>, T. Colombo<sup>58c</sup>, G. Colon<sup>86</sup>, G. Compostella<sup>101</sup>,  
P. Conde Muiño<sup>126a,126b</sup>, E. Coniavitis<sup>48</sup>, M.C. Conidi<sup>12</sup>, S.H. Connell<sup>147b</sup>, I.A. Connelly<sup>77</sup>,  
S.M. Consonni<sup>91a,91b</sup>, V. Consorti<sup>48</sup>, S. Constantinescu<sup>26a</sup>, C. Conta<sup>121a,121b</sup>, G. Conti<sup>57</sup>,  
F. Conventi<sup>104a,i</sup>, M. Cooke<sup>15</sup>, B.D. Cooper<sup>78</sup>, A.M. Cooper-Sarkar<sup>120</sup>, N.J. Cooper-Smith<sup>77</sup>,  
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A. Cortes-Gonzalez<sup>12</sup>, G. Cortiana<sup>101</sup>, G. Costa<sup>91a</sup>, M.J. Costa<sup>169</sup>, D. Costanzo<sup>141</sup>, D. Côté<sup>8</sup>,  
G. Cottin<sup>28</sup>, G. Cowan<sup>77</sup>, B.E. Cox<sup>84</sup>, K. Cranmer<sup>110</sup>, G. Cree<sup>29</sup>, S. Crépé-Renaudin<sup>55</sup>,  
F. Crescioli<sup>80</sup>, W.A. Cribbs<sup>148a,148b</sup>, M. Crispin Ortuzar<sup>120</sup>, M. Cristinziani<sup>21</sup>, V. Croft<sup>106</sup>,

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A. Dafinca<sup>120</sup>, T. Dai<sup>89</sup>, O. Dale<sup>14</sup>, F. Dallaire<sup>95</sup>, C. Dallapiccola<sup>86</sup>, M. Dam<sup>36</sup>, A.C. Daniells<sup>18</sup>,  
M. Dano Hoffmann<sup>138</sup>, V. Dao<sup>48</sup>, G. Darbo<sup>50a</sup>, S. Darmora<sup>8</sup>, J.A. Dassoulas<sup>42</sup>, A. Dattagupta<sup>61</sup>,  
W. Davey<sup>21</sup>, C. David<sup>171</sup>, T. Davidek<sup>129</sup>, E. Davies<sup>120,d</sup>, M. Davies<sup>155</sup>, O. Davignon<sup>80</sup>,  
A.R. Davison<sup>78</sup>, P. Davison<sup>78</sup>, Y. Davygora<sup>58a</sup>, E. Dawe<sup>144</sup>, I. Dawson<sup>141</sup>,  
R.K. Daya-Ishmukhametova<sup>86</sup>, K. De<sup>8</sup>, R. de Asmundis<sup>104a</sup>, S. De Castro<sup>20a,20b</sup>, S. De Cecco<sup>80</sup>,  
N. De Groot<sup>106</sup>, P. de Jong<sup>107</sup>, H. De la Torre<sup>82</sup>, F. De Lorenzi<sup>64</sup>, L. De Nooij<sup>107</sup>, D. De Pedis<sup>134a</sup>,  
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T. Del Prete<sup>124a,124b</sup>, F. Deliot<sup>138</sup>, C.M. Delitzsch<sup>49</sup>, M. Deliyergiyev<sup>75</sup>, A. Dell'Acqua<sup>30</sup>,  
L. Dell'Asta<sup>22</sup>, M. Dell'Orso<sup>124a,124b</sup>, M. Della Pietra<sup>104a,i</sup>, D. della Volpe<sup>49</sup>, M. Delmastro<sup>5</sup>,  
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A. Di Domenico<sup>134a,134b</sup>, C. Di Donato<sup>104a,104b</sup>, A. Di Girolamo<sup>30</sup>, B. Di Girolamo<sup>30</sup>,  
A. Di Mattia<sup>154</sup>, B. Di Micco<sup>136a,136b</sup>, R. Di Nardo<sup>47</sup>, A. Di Simone<sup>48</sup>, R. Di Sipio<sup>20a,20b</sup>,  
D. Di Valentino<sup>29</sup>, F.A. Dias<sup>46</sup>, M.A. Diaz<sup>32a</sup>, E.B. Diehl<sup>89</sup>, J. Dietrich<sup>42</sup>, T.A. Dietzsch<sup>58a</sup>,  
S. Diglio<sup>85</sup>, A. Dimitrievska<sup>13a</sup>, J. Dingfelder<sup>21</sup>, C. Dionisi<sup>134a,134b</sup>, P. Dita<sup>26a</sup>, S. Dita<sup>26a</sup>,  
F. Dittus<sup>30</sup>, F. Djama<sup>85</sup>, T. Djobava<sup>51b</sup>, J.I. Djuvsland<sup>58a</sup>, M.A.B. do Vale<sup>24c</sup>,  
A. Do Valle Wemans<sup>126a,126g</sup>, D. Dobos<sup>30</sup>, C. Doglioni<sup>49</sup>, T. Doherty<sup>53</sup>, T. Dohmae<sup>157</sup>,  
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D. Duda<sup>177</sup>, A. Dudarev<sup>30</sup>, F. Dudziak<sup>64</sup>, L. Duflot<sup>117</sup>, L. Duguid<sup>77</sup>, M. Dührssen<sup>30</sup>,  
M. Dunford<sup>58a</sup>, H. Duran Yildiz<sup>4a</sup>, M. Düren<sup>52</sup>, A. Durglishvili<sup>51b</sup>, M. Dwuznik<sup>38a</sup>, M. Dyndal<sup>38a</sup>,  
J. Ebke<sup>100</sup>, W. Edson<sup>2</sup>, N.C. Edwards<sup>46</sup>, W. Ehrenfeld<sup>21</sup>, T. Eifert<sup>145</sup>, G. Eigen<sup>14</sup>,  
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M. Ernst<sup>25</sup>, J. Ernwein<sup>138</sup>, D. Errede<sup>167</sup>, S. Errede<sup>167</sup>, E. Ertel<sup>83</sup>, M. Escalier<sup>117</sup>, H. Esch<sup>43</sup>,  
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A. Favareto<sup>50a,50b</sup>, L. Fayard<sup>117</sup>, P. Federic<sup>146a</sup>, O.L. Fedin<sup>123,k</sup>, W. Fedorko<sup>170</sup>,  
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A.B. Fenyuk<sup>130</sup>, S. Fernandez Perez<sup>30</sup>, S. Ferrag<sup>53</sup>, J. Ferrando<sup>53</sup>, A. Ferrari<sup>168</sup>, P. Ferrari<sup>107</sup>,  
R. Ferrari<sup>121a</sup>, D.E. Ferreira de Lima<sup>53</sup>, A. Ferrer<sup>169</sup>, D. Ferrere<sup>49</sup>, C. Ferretti<sup>89</sup>,  
A. Ferretto Parodi<sup>50a,50b</sup>, M. Fiascaris<sup>31</sup>, F. Fiedler<sup>83</sup>, A. Filipčić<sup>75</sup>, M. Filipuzzi<sup>42</sup>, F. Filthaut<sup>106</sup>,  
M. Fincke-Keeler<sup>171</sup>, K.D. Finelli<sup>152</sup>, M.C.N. Fiolhais<sup>126a,126c</sup>, L. Fiorini<sup>169</sup>, A. Firan<sup>40</sup>,  
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P. Fleischmann<sup>89</sup>, S. Fleischmann<sup>177</sup>, G.T. Fletcher<sup>141</sup>, G. Fletcher<sup>76</sup>, T. Flick<sup>177</sup>, A. Floderus<sup>81</sup>,  
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S. Franchino<sup>30</sup>, D. Francis<sup>30</sup>, L. Franconi<sup>119</sup>, M. Franklin<sup>57</sup>, S. Franz<sup>62</sup>, M. Fraternali<sup>121a,121b</sup>,  
S.T. French<sup>28</sup>, C. Friedrich<sup>42</sup>, F. Friedrich<sup>44</sup>, D. Froidevaux<sup>30</sup>, J.A. Frost<sup>28</sup>, C. Fukunaga<sup>158</sup>,  
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